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System for transmission of electric power

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TECHNICAL FIELD.

The invention relates to AC transmission cable systems for
power transmission within and between power networks. In
particular, the system is concerned with minimising power
10   losses associated with power transmission due to effects of
reactive charging losses as well as resistive and dielectric
losses.

BACKGROUND ART

15   Energy transmission by means of power cables is of particular
importance applied in densely populated areas and when passing
over stretches of open water. In densely populated areas land
values, reliability and aesthetic factors have great importance
whereas for passage over open water the costs of building large
20   number of pylon foundations is what steers the choice towards
cable solutions. The problem with extending existing
transmission cable installations is principally with generation
and transport of reactive power. The risks of resonance
problems for very long cable connections as a result of
25   harmonics in the power network also needs to be reduced. Losses
due to currents induced in the cable screen can also affect the
maximum transmission length for cable circuits.

With shorter transmission cable circuits of less than, say
30   50km, shunt compensation is used in order to compensate for the
cable losses due to capacitive generation effects. Sometimes an
additional dynamic compensation in the form of SVC, Static Var
Compensation, is required. The shunt compensation devices are
usually installed at both ends of the cable. There are also
35   examples of installations where shunt compensation devices are

2

cables circuits longer than approximately 50 km or so only
exist for low voltage levels (typically <100 kV) and low power
(<100 MVA). High voltage direct current (HVDC) installations
are today used almost exclusively for long power cable
5   transmission circuits.

SUMMARY OF THE INVENTION
The present invention solves one or more of the above problems.
In a first aspect of the invention an AC transmission cable
10   system is provided which comprises at least one transformer
arranged for a wide range of voltage transformation and capable
of being regulated such that the voltage across the
transmission reach may be varied so as to optimise the
instantaneous power transmitted to a level of a natural load
15   for the cable in use. The natural load is defined to be the
load when the cable system in principle does not absorb or
generate reactive power at either end. The term cable system is
used to designate one or several reaches of power cable and
shunt reactors connected at the joints between cable reaches.
20   Shunt reactors at the cable terminal may or may not be included
in the cable system. The AC transmission cable system described
is also capable of being regulated such that the voltage across
the transmission reach may be varied so as to reduce dielectric
and resistive losses to a minimum. The AC transmission cable
25   system described comprising also associated joints, terminals,
breakers and protection devices is further capable of being
regulated such that voltage across the transmission reach may
be varied so as to minimise no-load power losses.

30   In another aspect of the invention a method is described for
regulating the AC transmission cable system at a voltage that
dependent on the natural load of the cable thus minimising
reactive power losses, dielectric losses and resistive losses,
especially under no-load conditions.

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3

In another further aspect of the invention the short circuit current through the invention is reduced at low power flow loads. The tap changing will increase the cable impedance according to the square of the tap ratio. The invented cable
5   system will therefore not contribute as much as today's solution to short circuit currents. This means that more circuits can be parallelized during low load increasing the reliability of electric energy supply.

10   In another, further aspect of the invention a control and communication system is described for carrying out communication and control functions actions of the methods for regulating the AC transmission cable system at a voltage that is dependent on the load of the cable.
15

In yet another, further aspect of the invention a graphical user interface (GUI) is described for displaying operating parameters of the described AC transmission system.

20   In order to minimize reactive power losses, the invention uses an effect or a phenomenon known as the Natural Load or Surge Impedance loading for a transmission conductor, which is defined (see definition above) and may be expressed as:

$$P_{natural} = \frac{V^2}{Z_v} \qquad\qquad (0)$$

25   where V is voltage and Z_v is (the real part of) the surge impedance. This load level is especially beneficial where the transmission cable consumes the same amount of reactive power per unit length as it generates. Reactive power therefore does not need to be transmitted in any direction. By taking the
30   power flow through the cable reach at the level of P_{actual} the cable can be operated at natural load by means of regulating the voltage level V according to an equation such as:

$$V = \sqrt{Z_v \cdot P_{actual}}$$

4

The Figures 5 A, B, C, D shows an example of an 130 kV circuit. It may be operated in either of two modes. The first mode A, B is in a conventional way of the Prior Art, which means held at a constant voltage all the time. The second mode is in a

5 voltage dependent mode, "Voltage Dependent Cable Transmission (VDCT)", that is according to the invention and equation (0) above. In the lower right corner of Figure 5 in the plot D we can see that the conventional operation in this case will generate some 40 MVAr capacitive power in each end which must

10 be compensated for. This compensation also causes further electrical losses that occur in the reactors. The voltage dependent cable transmission of the invention almost balances the reactive production by varying the voltage. Any discrepancy is due to the resistive voltage drop in the cable reach. The

15 invention therefore reduces unnecessary reactive power production and thereby decreases the resistive losses associated with this unnecessary transport. However, as well as the resistive losses, there are also considerable losses due to dielectric effects in the cable and to resistive losses in the

20 compensation equipment, typically reactors. These losses can also be minimised according to the present invention.

The relation between resistive losses and dielectric losses may be calculated. The following calculation, for example, is valid

25 for a single point along an AC transmission circuit:
In the calculation of cable voltage optimisation at a point, we considered a power cable that can operate at variable voltage as described above and in equation (1) and derive the optimal cable voltage. We are assuming that the total active cable

30 losses are equal to the sum of resistive losses and dielectric losses. We assume that the resistive losses are proportional to the square of the current and the dielectric losses are proportional to the square of the voltage. In this study, we introduce the following quantities:

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U_n is the rated voltage of the cable [V]

I_n is the rated current of the cable [A]

S_n is the rated apparent power $S_n = U_n I_n$ of the cable [VA]

P_f is the total losses [W]

P_{fd} is the dielectric losses at rated voltage [W]

P_{fr} is the resistive losses at rated current [W]

P_{fn} is the total losses at rated current and rated voltage [W]

We introduce the following non-dimensional quantities:

x is the non-dimensional voltage U/U_n

y is the non-dimensional current I/I_n

s is the non-dimensional apparent power S/S_n

z is the non-dimensional losses P_f/S_n

c is the relative dielectric losses P_{fd}/P_{fn}

5 Equation (1) gives the non-dimensional cable losses:

$$z = cx^2 + (1-c)y^2 \tag{1}$$

We want to minimize z subject to the following restrictions:

$$xy = s \tag{2}$$

$$x_m \leq x \leq 1 \tag{3}$$

$$y \leq 1 \tag{4}$$

We combine equation (1) and (2) to obtain:

$$\tag{5}$$

$$z = cx^2 + (1-c)\frac{s^2}{x^2}$$

Now we differentiate (5) with respect to x and obtain:

$$\tag{6}$$

$$\frac{dz}{dx} = 2cx - 2(1-c)\frac{s^2}{x^3}$$

6

A necessary condition for extremum is that $dz/dx = 0$, which gives:

$$cx^4 = (1-c)s^2 \tag{7}$$

The preliminary result, which does not reflect the restrictions (3) and (4) is:

$$x_1 = \sqrt[4]{\frac{1-c}{c}s^2} \tag{8}$$

5   To show that equation (8) gives a minimum value we calculate the second derivative of the losses by differentiating equation (6) with respect to z.

$$\frac{d^2z}{dx^2} = 2c + 6(1-c)\frac{s^2}{x^4} \tag{9}$$

Now we combine equation (8) and equation (9) to obtain:

$$\frac{d^2z}{dx^2} = 2c + \frac{6(1-c)s^2c}{(1-c)s^2} = 2c + 6c = 8c > 0 \tag{10}$$

10   The second derivative of the losses with respect to voltage is always greater than zero and equation (8) gives the minimum losses. We may presume that the unconstrained minimum is not always a feasible solution that takes into account that we have a limited regulating range $x_m < x < 1$ for the voltage and an
15   upper limit $y < 1$ for the current. First, we modify the preliminary voltage given by equation (8) with respect the voltage limits.

$$x_2 = \min\left[\max(x_1, x_m), 1\right] \tag{11}$$

We may now calculate a preliminary current as follows.

$$y_1 = \frac{s}{x_2} \tag{12}$$

Now, we modify this preliminary current with respect to the
20   current limit.

$$y = \min(y_1, 1) \tag{13}$$

7

We may now calculate the final value of the cable voltage as follows: (14)

$$x = \frac{s}{y}$$

Figure 7 shows the optimal voltage as a function of cable
5   loading. Balanced losses mean that the resistive losses are
equal to the dielectric losses at rated current and rated
voltage ($c = 0.5$). Low dielectric losses means that $c = 0.2$ while
low resistive losses means that $c = 0.8$.

Figure 8 shows the optimal current as a function of cable
10   loading, see Balanced Losses.

Figure 9 shows the Resistive and dielectric losses as a
function of cable loading.

Figure 10 shows the loss reduction for a cable with low
Dielectric Losses.

15   Figure 11 shows the loss reduction for a cable with balanced
losses for Constant voltage, Variable voltage respectively.

Figure 12 shows the Loss reduction for a cable with high
dielectric losses for Constant voltage, Variable voltage
respectively.

If we study the whole cable, Equation 2 becomes

$$xy = s(d)$$

where d is the distance from one end. We minimize the function

$$\int_0^{length} s(d)dd$$

with respect to voltage and end up with the operating voltage of
the cable transmission system

8

The overall conclusion as a result of this combined minimisation of the unnecessary reactive power flow, and the optimal voltage to reduce dielectric and resistive losses, calculated for one point in the cable, will give a minimum of total losses in the
5   transmission cable.

The principal advantage of the invention is that minimal power losses due to reduced dielectric and resistive losses mean that the length of an AC transmission cable reach according to the
10   invention is not limited to around 50 km or so but may in fact be several hundred kilometres in length. This is so because the in the prior art method and system of shunt reactors to compensate for reactive power generation are only effective for a circuit lengths of up to 50 km or so as the resistance and
15   impedance of the circuit is a function of the circuit length. For the invention, no reactive power is transmitted and so no shunt reactors are required to compensate, thus there is virtually no limit to circuit length caused by generation or transport of reactive power. This provides then AC power
20   transmission cable systems with significantly lower power losses in operation that may link together power networks which are hundreds of kilometres apart in a way that is more economical to build   than the Prior Art, which has to have reactive power compensation equipment installed at least every
25   50 km or so.

Another advantage of the invention is that reactive power compensation by shunt reactors is not required at the ends of a transmission circuit or, even more disadvantageously, at
30   intervals along the length of a prior art circuit. Instead, a transformer with wide transformation variability is required at each end of the circuit, and the circuit has to be operated with variable voltage. A transformer of some sort is almost always required at the end of a transmission circuit, so that
35   an installation according to the invention is both less

9

expensive to build and, with significantly lower power losses, less expensive to operate. Reactive power shunt reactors also have power losses associated with them.

5   For example, the power loss due to dielectric and charging power losses for an AC transmission cable under no-load are reduced by as much as one-third or more, which, when the number of many power networks that are run at no-load every night is taken into consideration, provides a great environmental and

10   economic benefit. Further, in a particular embodiment of the invention a wide range transformer may only be required at one end of the transmission circuit.

Another advantage of the invention is that the thermal overload

15   capacity of the cable in a transmission circuit described is greater than for Prior Art cable systems. This permits greater freedom in running under temporary overloads to ease problems in a power network.

20   BRIEF DESCRIPTION OF THE DRAWINGS
A more complete understanding of the method and system of the present invention may be had by reference to the following detailed description when taken in conjunction with the accompanying drawings wherein:

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Figure 1a shows in a simplified diagram an example of an HV AC cable transmission circuit for a system between two points connected to power networks according to the Prior Art; Figure 1b shows a simplified diagram for a system with an HV AC cable

30   transmission circuit and a transformer according to the Prior Art, and Figure 1c shows a similar diagram for a system with a transmission cable and one transformer. Figure 1d shows a simplified diagram for a HVDC cable system with a transmission cable and two AC/DC rectifiers according to the Prior Art.

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Figure 2 shows schematically a system comprising a transmission circuit and two transformers arranged between two points connected to power networks according to an embodiment of the invention;

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Figure 3 shows in a schematic diagram system with an HV AC cable transmission circuit and two shunt reactors arranged between two points connected to power networks according to the Prior Art;

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Figure 4 shows schematically a system comprising a transmission circuit and two variable transformers arranged between two points connected to power networks according to an embodiment of the invention;

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Figure 5 C, D show characteristic operating values for an AC cable reach according to the Prior Art; and Figure 5 A, B shows the corresponding operating values for an AC transmission reach according to an embodiment of the invention;

20

Figure 6 shows a system with two parallel AC transmission cables and two fast-acting breakers connected between two points A, B to power networks according to another embodiment of the invention;

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Figures 7-12 show characteristic operating parameters calculated about a point in an AC transmission reach according to an embodiment of the invention;

30   Figure 13 shows schematically a system with a transmission circuit between two points connected to power networks using an HV transmission cable and only one wide range transformer according to another embodiment of the invention;

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Figure 14 shows schematically a system including a transmission circuit and at least three transformers arranged between more than two points each connected to power networks according to another embodiment of the invention;

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Figure 15 shows schematically a graphic user interface for displaying operating parameters of the described AC transmission system and/or to carry out one or more methods of the invention.

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DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 a (Prior Art) shows a HVAC transmission cable of which the nominal operating voltage V_{n1} is the same at both ends of the line. If the nominal operating voltage at each end is not

15   the same, $V_{n1} \neq V_{n2}$, one possible Prior Art arrangement is shown in Figure 1b, where the operating voltage for the cable is V_{n1} and a transformer is installed at one end of the cable. Figure 1c shows the same arrangement except for that the nominal operating voltage for the cable is V_{n2}. If the distance for AC

20   transmission between terminal points is too great, HVDC technology may be used, as shown in Figure 1d. In this Prior Art arrangement the problem of reactive power losses is overcome by rectifying from AC to DC current.

25   Figure 2 shows an embodiment according to the present invention. It can be seen by comparing the invention of Fig 2 to the prior art arrangements illustrated in Figures 1a-d that the cable voltage in the system according to the invention does not necessarily have to be the same as one of the nominal

30   operating voltages V_{n1}, V_{n2}, of the connection points. Operating voltage can vary over a large range not necessarily the same as either V_{n1} and/or V_{n2}. The operating voltage of the cable may vary during power transmission operation and, with coordinated control of the tap changers or equivalent in the transformers

12

resistive losses can be minimized, as will also dielectric
losses which will be more fully described below.

Figure 3 (Prior Art) shows a transmission circuit 1 arranged

5   between two points A, B, including an AC cable and two shunt
reactors 2_A, 2_B for compensation of reactive power.

Figure 4 shows a transmission circuit 1 according to an
embodiment of the invention. The transmission circuit 1 is

10 arranged between two points A, B. Two transformers 3_A, 3_B with
variable turn ratios are shown, one at each end of the cable 4
reach.

When voltage is dynamically regulated with the goal of

15 operating a cable reach at Natural Load under as greater part
of the time as possible then shunt compensation of the Prior
Art such as Figure 3 can be avoided. The voltage is adjusted
with the help of two transformers 3_A, 3_B each with voltage
transformation variable between 1:1 and typically 1:2 with the

20 aid of tap changers. Because natural load varies according to
the square of the voltage the variable voltage transformation
makes it possible to vary the natural load in the interval from
25 to 100% of the natural load at highest voltage for
equipment. Low load conditions, for example during a summer

25 night in Sweden, are about 1/4 of the maximum load during a
winter day which, in principle, is covered by the indicated
transformation ratios. At the same time it is possible to add a
phase shifting tap changer in order to increase the ability to
regulate active effect.

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The solution according to the invention may advantageously use
autotransformers in those situations where the nominal voltage
levels between the two ends of the cable reach are not very
great.   Methods to limit the short-circuit currents at voltage

13

transformations of 1:1 for an autotransformer may be introduced
if found necessary.

A problem with existing transmission cables is that surge
5   impedance is relatively low which gives a high natural load in
relation to the cable diameters that are practical or preferred
for manufacturing reasons. Therefore it is possible and would
be preferable to influence the natural load level of cables by
adjusting the surge impedance of the cables to a favourable
10   value.

One can further carry out parts of the adjustment between
higher and lower voltages in greater steps with the aid of one
or more breakers, preferably of the fast-acting type. Figure 4
15   shows schematically another embodiment and system in which it
is possible with two parallel cables to rapidly dis-connect and
re-connect one of the cables upon the occurrence of transients
in the power network.

20   Figure 6 shows two parallel AC cables, 4a, 4b, arranged with
fast acting breakers 5_A, 5_B connected between two points A, B.
An autotransformer 3_A, 3_B is shown at each end A, B of the
reach. In each autotransformer a rapid by-pass member 7, 8 is
shown. These by-pass switches may be designed so as to manage
25   any turn-to-turn short circuits that may occur within the
transformer due to these switches. Similar designs as for tap
changers may be necessary. Where the autotransformer comprises
a tap changer, then the rapid by-pass member is an electro-
mechanical device arranged to by-pass or short circuit one or
30   more taps very rapidly. Where the tap changer is of the
electronic type, IGBT based or similar, the rapid by-pass
member is not required. Thus, parts of the transformer winding
may be by-passed so as to compensate quickly for the change.
When using a transformer equipped with a tap changer the

14

mechanical movements necessary to switch between one point in
the windings and another take a finite amount of time.

These methods are also useable if the flow of power through the
5 transmission cable reach increases or decreases transiently.
The voltage level of the power transmission then requires a
relatively fast adjustment to the new power level. The speed of
adjustment required is difficult to achieve with electro-
mechanical tap changers. It is preferable for the cable reach
10 system to uses electronic tap changers, for example IGBT, IGCT,
GTO or thyristor-based solutions, so that the disconnect and
re-connect can be carried out with satisfactory speed.

Figure 11 shows an AC transmission circuit between two points
15 A, B' connected to power networks using only one wide range 3_A
transformer. At the other end B' the cable reach is connected
via a transformer 10 without any tap changer to one or more
electrical machines that are electrically isolated from the
rest of the system, in this example, wind generators or wind
20 turbines of a Wind Park 11. In this alternative embodiment the
transformer 3_A at network end A regulates the voltage in the way
described in this description. At the other end, the electrical
machines in the wind park control their output voltage level so
as to minimize losses of power transfer between the wind park
25 11 and point A. A benefit of this arrangement is that the cable
reach from, say, a wind park to an electrical grid may be
constructed for distances greater than 50 km, run at minimized
dielectric and resistive losses and require the provision of
only one tap changer equipped transformer 3_A. By means of this
30 alternative embodiment of the invention a wind park of a given
MVA output may provide a much greater net power than prior art
arrangements delivered to the power network. Separate voltage
control of each wind turbine is possible with full power
electronic converters connected in series with the wind
35 turbine, by means of a double fed induction machine or a

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synchronous generator. Coordinated control between the tap changer transformer and the individual wind turbines is possible where a central computer calculates the cable operating voltage giving the lowest losses. Due to varying
5   power production from the wind farm it is likely that the range is larger than 1:1 to 1:2 of the tap changer transformer.

A second source of power losses in a power cable is dielectric losses, typically primarily dependent on heat or polarisation
10   losses within the cable insulation. Here below follows an example calculated on the basis of an existing power transmission cable in Scandinavia.

Generally speaking the dielectric losses are approximately
15   proportional to the square of the voltage. The invention also reduces these losses by operating at a lower voltage level. A simple numerical demonstration of this may be calculated in reference to a 400 kV mass-impregnated AC-cables between Sweden and the island of Zealand (Denmark) as an example:

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Oil-Paper cable
420 kV operating voltage
870 MVA power transmitted
11.4 km long
25   1200 A rated current
Conductor losses: 32.8 kW/km and phase, 85 degrees
Sheath and Armouring losses: 34 kW/km and phase
Dielectric losses: 8.4 kW/km and phase
(See reference [1] page 340, equations 12.37, 12.39)
30   1. Assume that resistive losses in conductor and sheet are proportional to current squared:

$$I_c = 2\pi f C U_0$$

where I_c is the charging current, f is the system frequency, C is cable capacitance and U_0 (V) is the phase-to-ground voltage.

16

2. The charging losses are then (from [1])

$$W_{ch} = 2\left[\frac{1}{3}I_c^2\left(\frac{L}{2}\right)^3 \cdot R\right]$$

where W_{ch} are the charging losses, and R is the resistance of
the cable.

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At maximum load we have 75.2 kW/phase, km losses
This gives a resistance of (32.8+34)/1200^2=0.0464 Ohm
Then we have for todays no-load situation:
Charging current=17.5 A/phase
10   Charging losses=2*1/3*17.5^2*(11.4/2)^3*0.0464=1754 kW, phase
Dielectric losses=11.4*8.4=95 kW/phase
The cable produces 11.4*17.5*sqrt(3)*420= 145 MVAr
This corresponds to 1450 kW in SVC losses
Current at connection point= 17.5*11.4/2=100 A/phase
15   Total losses at no load= 6.9 MW

If we reduce operating voltage from 420 to 300 kV, we arrive
at:
Charging current=12.5 A/phase
20   Charging losses=2*1/3*12.5^2*(11.4/2)^3*0.0464=894 kW, phase
Dielectric losses=11.4*4.3=49 kW/phase
The cable produces 11.4*12.5*sqrt(3)*300= 74 MVAr
This corresponds to 377 kW in SVC losses
Current at connection point= 12.5*11.4/2=71 A/phase
25   Total losses at no load= 3.2 MW

If we reduce operating voltage further to 200 kV,
we arrive at:
Charging current=9.75 A/phase
30   Charging losses=2*1/3*9.75^2*(11.4/2)^3*0.0464=544 kW, phase
Dielectric losses=11.4*1.9=22 kW/phase
The cable produces 11.4*9.75*sqrt(3)*200= 39 MVAr
This corresponds to 104 kW in SVC losses

17

Total losses at no load= **1.8 MW**

The savings in terms of power that no longer has to be
generated to feed the normal losses under no-load are clearly
5   very great. This example demonstrates that a transmission cable
arranged according to the invention would consume no-load
losses of only about one-third, or less, of an existing
transmission cable reach.

10   With the invented system arrangement and method of controlling
the voltage the reactive power flows can be drastically
reduced, and both resistive and dielectric losses can be
reduced.   Another important result is that the reduced no-load
losses will result in a slightly cooler cable. This can be
15   either be used to allow for temporary overload of the cable
i.e. introduce a temperature dependent dynamic rating, or
instead to reduce the specification and thereby material costs
and manufacturing costs for the cable.

20   The reactive power in this example, no load situation, is not
reduced to zero and it may not be practical to reduce voltage
further than a minimum level in other real cases. At low loads
the voltage optimisation may also be at a minimum voltage level
which is not equal to zero, such as the minimum level shown in
25   Figure 7.

The cable system may comprise standard equipment for AC
over-voltage protection and shielding. This may include for
example transposings and sheath sectionalizing insulators
30   fitted to the cables to reduce shield induced currents.
Similarly, to guard against known disturbances in long AC
circuits such as overtones the system may be equipped with a
high frequency filter such as for frequencies of around 100 Hz
or higher.

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18

Figure 14 shows an additional embodiment of the invention
wherein the inventive cable transmission system comprises a
third connection point.

5   Methods of the invention may also be practised, carried out,
monitored and implemented by means of a system for control
comprising a system for communication. Each of the two
transformers 3_A, 3_B are controlled and regulated in a
synchronous or coordinated manner to regulate the operating

10 voltage V of the AC transmission cable. Effective control is
enabled by means of high speed communication of data and values
for voltage and other parameters from and to control systems or
components for transformers located at any end of the AC
transmission cable. Such real time values for operating

15 parameters may be displayed by means of a Graphical User
Interface (GUI), a graphical or textual display on an operator
workstation, running on a user's logged-in computer, connected
direct to a local, central, regional or international power
network control system; or connected via a main or local

20 control server or other control system computer.

Figure 15 shows schematically an example for a graphical user
interface for displaying operating parameters of the described
AC transmission system and/or to carry out one or more methods

25 of the invention. The figure shows a GUI 20, comprising two
parts or panes, 21, 22. Pane 21 includes a schematic of two
variable transformers, 23_A, 23_B at either end of a cable reach
24, which corresponds with cable 4 in the invention as shown in
Figure 4. The GUI shows in panel 21 values such as a voltage 31

30 for the voltage at point B and temperatures such as temperature
30 for a temperature of a variable transformer 23_A. The GUI
shows in another window or panel, such as pane 22 another
schematic for a part of a network or for an installation. A
display in the form of a Windows NT type tree 25 includes
various installations and equipment, such as the A-B cable

19

reach 26 shown here as selected for access and thus shown in
detail in the second panel 21. An operator or a process running
in a computer may use the GUI interface and application to
examine data and values such as 30, 31 for a transmission cable
5   reach A-B, in particular one or more voltages and temperatures,
and carry out a control action. In a preferred embodiment one
of more object oriented control system applications of the
Industrial IT product range supplied by ABB may be used to
provide control and/or supervisory functions, and the necessary
10   GUI applications for presenting, displaying and generating such
relevant control actions.

It should be noted that while the above describes exemplifying
embodiments of the invention, there are several variations and
15   modifications which may be made to the disclosed solution
without departing from the scope of the present invention as
defined in the appended claims.

References

20   [1] Anders, George J., Rating of electric power cables:
ampacity calculations for transmission, distribution, and
industrial applications. Pages 340-341. IEEE Press power
engineering. ISBN 0-7803-1177-9

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CLAIMS

1. A high voltage AC transmission cable system (1) for transmitting power between two points (A, B) each connected to one or more power networks wherein at least one transformer is arranged at each end of an AC transmission cable, **characterised** in that at least one said transformer (3_A, 3_B) is arranged with a voltage control member capable of operating the transformer at a voltage whereby losses due to reactive power transport are minimized.

2. A system according to claim 1, **characterised** in that the system comprises a control member to operate said system at an optimal voltage dependent on the surge impedance of the cable (Z_V) and the instantaneous power level.

3. A system according to claim 1, **characterised** in that the system comprises a control member to operate said system at an optimal voltage dependent on an instantaneous power level equal to the Natural Load ($P_{natural}$) of the cable.

4. A system according to claims 1, **characterised** in that the system comprises a control member to operate said system at a voltage whereby the sum of the resistive losses, dielectric losses and charging losses are minimized.

5. A system according to any of claims 1-4, **characterised** in that the control member is arranged for communication with control equipment at both ends of said AC transmission cable.

6. A system according to any of claims 1-5, **characterised** in that the control member is arranged with control instructions for operation of said AC transmission cable under thermal overload conditions during limited periods of time.

21

7. A system according to any of claims 1-6, **characterised** in that the at least one said transformer is arranged to operate with a wide ratio of input voltage to output voltage of between 1:1 to 1:2, or greater.

5

8. A system according to any of claims 1-6, **characterised** in that the voltage control member in at least one said transformer (3_A, 3_B) is arranged with a tap-changer.

10   9. A system according to claim 1, **characterised** in that the voltage control member is a power electronic device which may be any of the list of: IGBT, IGCT, GTO, Thyristor, Diode.

10. A system according to claim 1, **characterised** in that the
15   voltage control member is a mechanical tap-changer.

11. A system according to claim 10, **characterised** in that the tap-changer may further be a phase-shifting tap changer.

20   12. A system according to claim 1, **characterised** in that in that the voltage control member is comprised in an autotransformer.

13. A system according to claim 1, **characterised** in that the
25   voltage control member is an autotransformer.

14. A system according to claim 1, **characterised** in that the at least one transformer is arranged to limit short-circuit currents.

30

15. A system according to claim 1, **characterised** in that the system is equipped with a high frequency filter.

22

16. A system according to claim 1, **characterised** in that at least one transformer winding may be arranged for fast short-circuit of a part of the transformer windings.

5   17. A system according to claim 1, **characterised** in that the cable reach may comprise one or more parallel cables (4a, 4b) for each phase, wherein each cable is arranged for rapid dis-connect and re-connect.

10   18. A system according to claim 18, **characterised** in that the cable system may comprise one or more breakers (5_A, 5_B) arranged for rapid dis-connect and re-connect.

19. A system according to claim 18, **characterised** in that the
15   cable system may comprise one or more tap changer by-pass connectors (7, 8).

20. A system according to claim 1, **characterised** in that one or more AC transmission cables may be an oil and paper insulated
20   cable.

21. A system according to claim 1, **characterised** in that said one or more AC transmission cables may be an XLPE insulated cable.

25

22. A system according to claim 1, **characterised** in that the system may be equipped with one or more over-voltage protection devices, phase-to-phase, phase-to-earth, depending on the cable.

30

23. A system according to claim 1, **characterised** in that the cable system may be equipped with one or more ways of protecting the sheath from overvoltage.

23

24. A system according to claim 1, **characterised** in that the cable system shield may be equipped with transposings and sheath sectionalizing insulators reducing shield induced currents.

5

25. A system according to claim 1, **characterised** in that at one end of the cable reach may be connected to one or more electrical machines (11) isolated from the rest of the system.

10   26. A system according to claim 25, **characterised** in that a transformer (10) arranged nearest the electrical machines (11) has a fixed transformation ratio or is equipped with off-load tap-changers only.

15   27.   A system according to claim 25, **characterised** in that voltage regulation of the machines (11) is controlled according to the same natural load and minimize losses principle as it would be applied to a tap changer.

20   28. A method to control a high voltage AC transmission cable system for transmitting power between two points (A, B) connected to one or more power networks wherein at least one transformer (3_A, 3_B) is arranged at each end of an AC transmission cable (4), **characterised** by operating the cable
25   with a variable voltage (V) which may differ from a voltage of said one or more power networks.

29. A method according to claim 28, **characterised** by regulating the voltage dependant on a function of the natural load of a
30   said AC transmission cable, and so controlling the level of reactive power transported into any of said one or more power networks.

24

30. A method according to claim 28, **characterised** in that the voltage is regulated dependent on the natural load whereby losses at due to resistive, dielectric effects are minimised.

5   31. A method according to claim 30, **characterised** in that the voltage is regulated under no-load conditions so that losses are reduced while maintaining voltage above a lower, minimum voltage level depending on system conditions.

10   32. A method according to claim 30, **characterised** in that the voltage is regulated under low load conditions so that losses are reduced while maintaining voltage above a lower, minimum voltage level depending on system conditions.

15   33. A method according to claim 28, **characterised** in that the voltage is regulated dependent in part on an equation of the form:

$$V = \sqrt{Z_v \cdot P_{actual}}$$

where V is voltage, Z_v is the real part of the surge impedance
20   and P_{actual} is the present active power flow.

34. A method according to claim 28, **characterised** in that the voltage is regulated dependent on thermal overload limits for the transmission cable (4) during limited periods of time.

25

35. A method according to claim 28, **characterised** by rapidly re-connecting and disconnect supply to and from at least two transmission cables (4a, 4b).

30   36. A method according to claim 28, **characterised** in that the voltage is regulated by more than one said transformer (3_A, 3_B) which are operated synchronously with each other.

37. Use of a high voltage AC transmission cable system for

25

claims 1-27 as a power feeder for large, densely populated urban or suburban areas.

38. Use of a high voltage AC transmission cable system for
5   transmitting power over a distance between two points (A, B) according to claims 1-27 in which a part of the distance is across water.

39. Use of a high voltage AC transmission cable system for
10 transmitting power between two points (A, B) according to claims 1-27 wherein one point comprises one or more electrical machines isolated from an electrical power network.

40. A system for communication and control for a high voltage
15 AC transmission cable system for transmitting power between two points (A, B) connected to one or more power networks wherein high speed data communication members are arranged for communication with control equipment for at least one transformer (3_A, 3_B) arranged at at least one end (A, B) of an
20 AC transmission cable (4).

41. A graphical user interface (20) for controlling a high voltage AC transmission cable system for transmitting power between two points (A, B) connected to one or more power
25 networks wherein at least one transformer (3_A, 3_B) is arranged at each end of an AC transmission cable (4), **characterised by** at least one object oriented applications for presenting data, parameter values and control actions for operating parameters (30, 31) of the AC transmission cable system and/or a control
30 system for at least one transformer (3_A, 3_B).

26

ABSTRACT

The invention concerns a high voltage AC transmission cable
system for transmitting power between two points, each
connected to one or more power networks, and a method to

5   operate the system. At least one transformer is arranged at
each end of the AC transmission cable, wherein at least one
said transformer is arranged to operate the transformer at a
voltage whereby losses due to reactive power transport and
dielectric losses are minimized. The AC cable is run at a

10 variable voltage regulated such that the voltage is a function
of the load for the transmission cable. This operating voltage
is not necessarily the same as the nominal voltages in the
connection points. In other aspects of the invention a control
and communication system and a graphical user interface for

15. carrying out the method is described.

(Figure 2)

1/8

V_{n1} V_{n1}

1a

V_{n1} V_{n2}

V_{n1}

1b

V_{n1} V_{n2}

V_{n2}

1c

V_{n1} V_{n2}

AC/DC   DC/AC

1d

Figure 1a-d Prior Art

V_{n1} V_{n2}

Voltage can vary over a wide range
not necessarily the same as $V_{n1},$
V_{n2}

Figure 2

2/8

A —————— Long AC Cable —————— B

1

Shunt reactors

2_A 2_B

Figure 3 Prior Art

A   Long AC Cable   B

1

4

3_A 3_B

Variable transformers
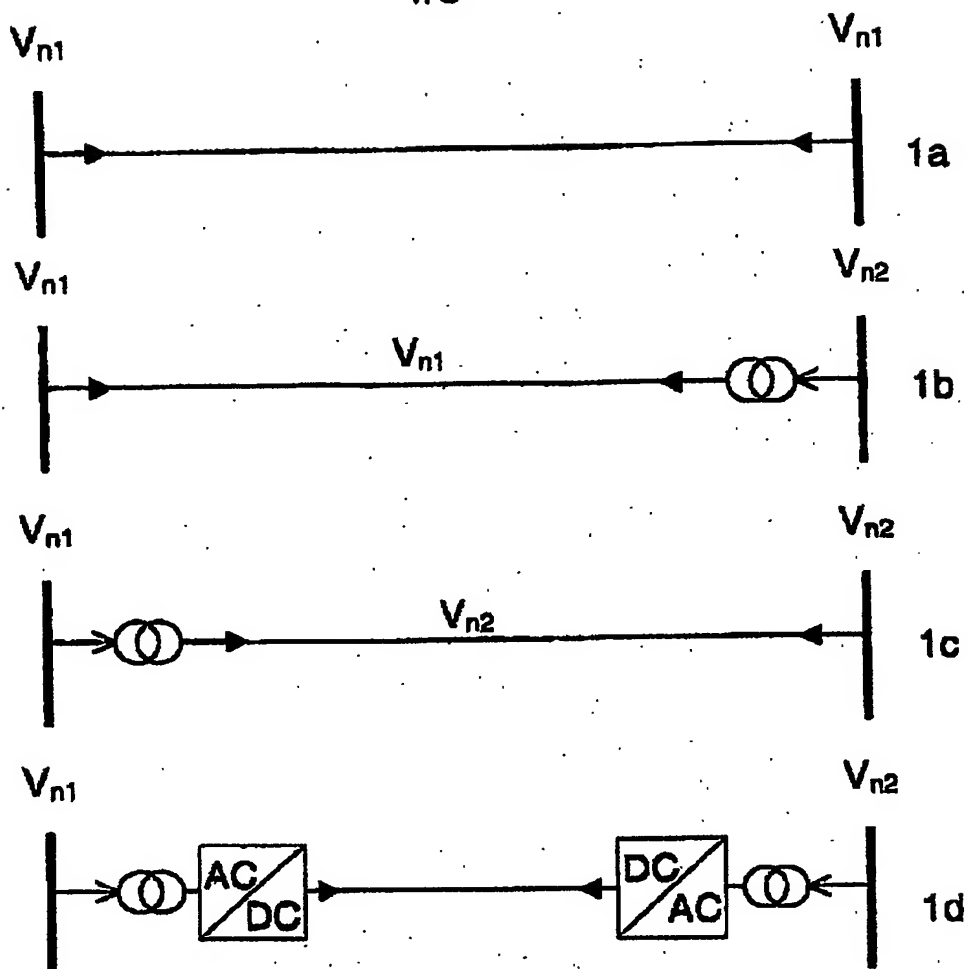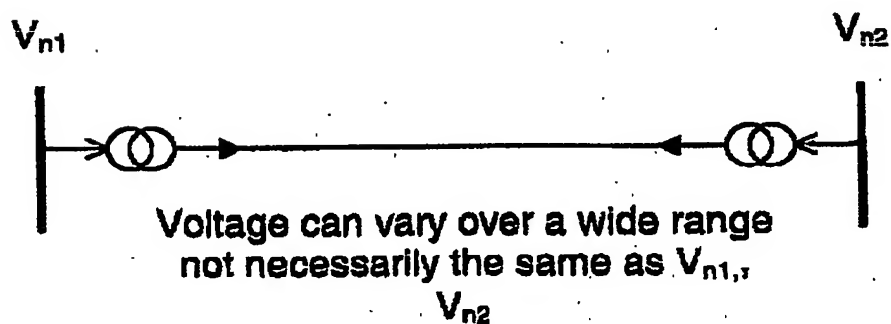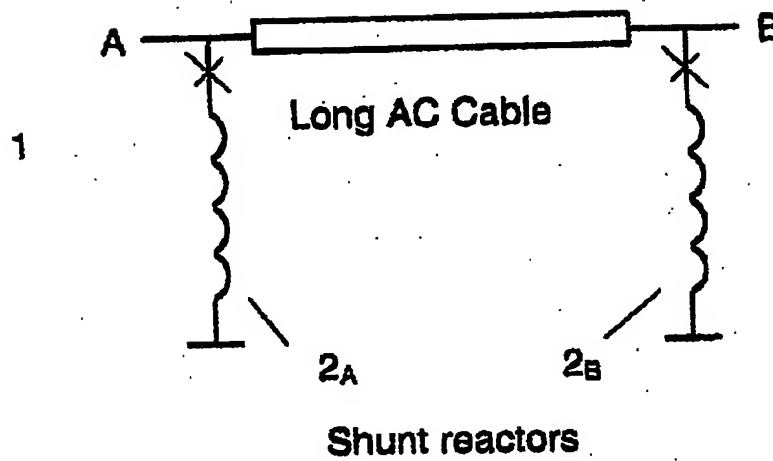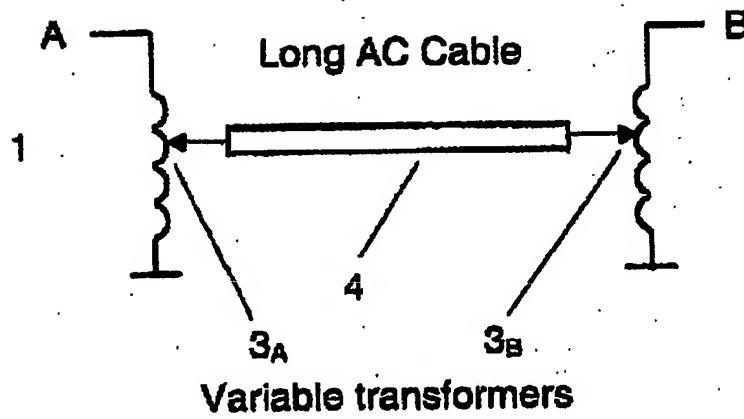
Figure 4

3/8
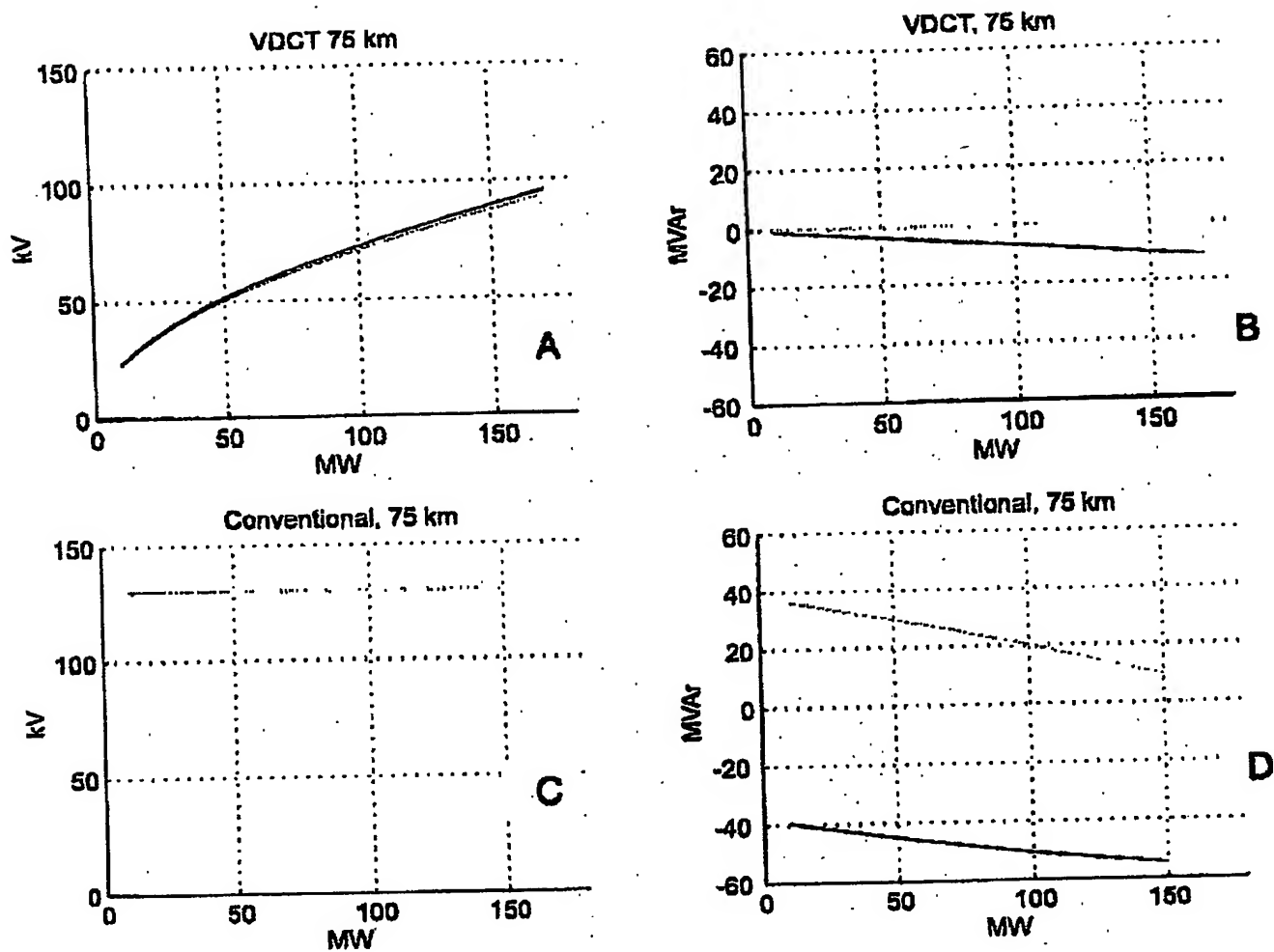
Figure 5

4/8
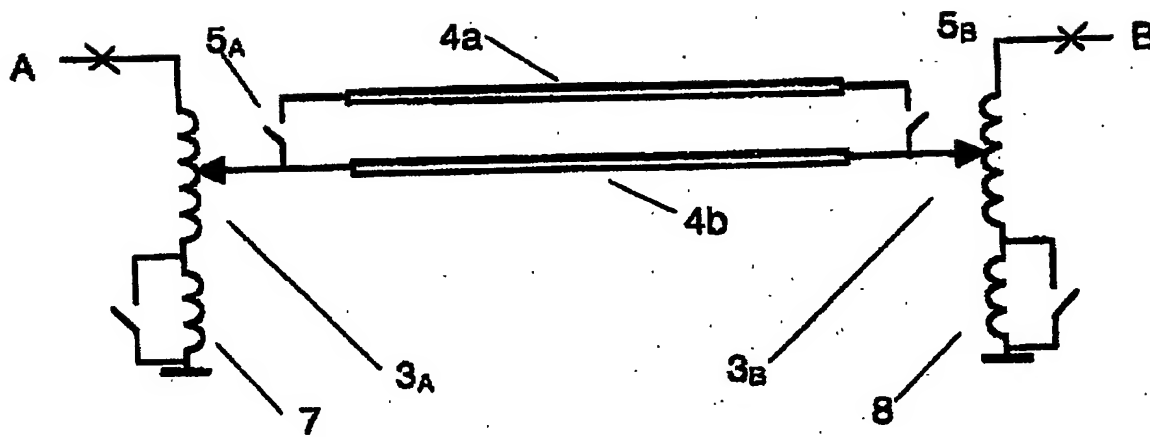
Figure 6

Cable Voltage Optimization
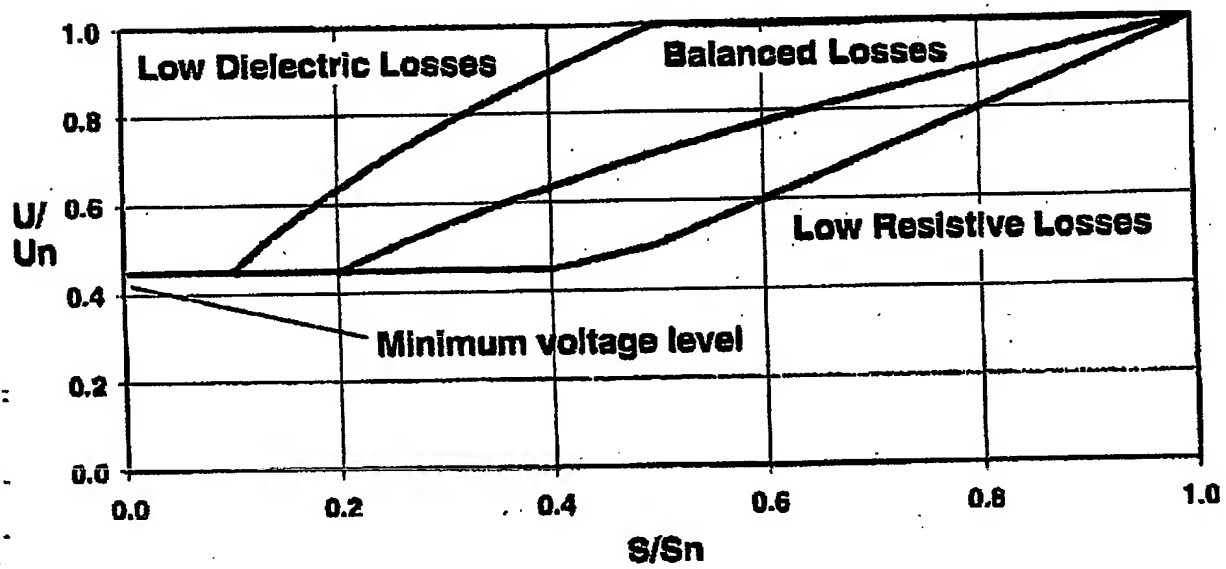
Figure 7

5/8

Cable Voltage Optimization
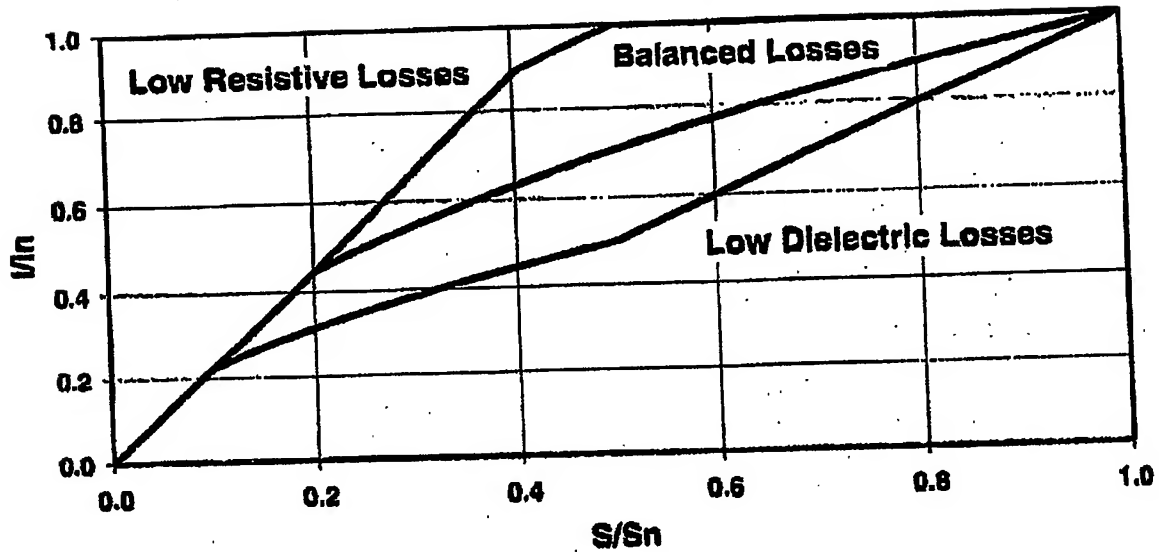
Figure 8

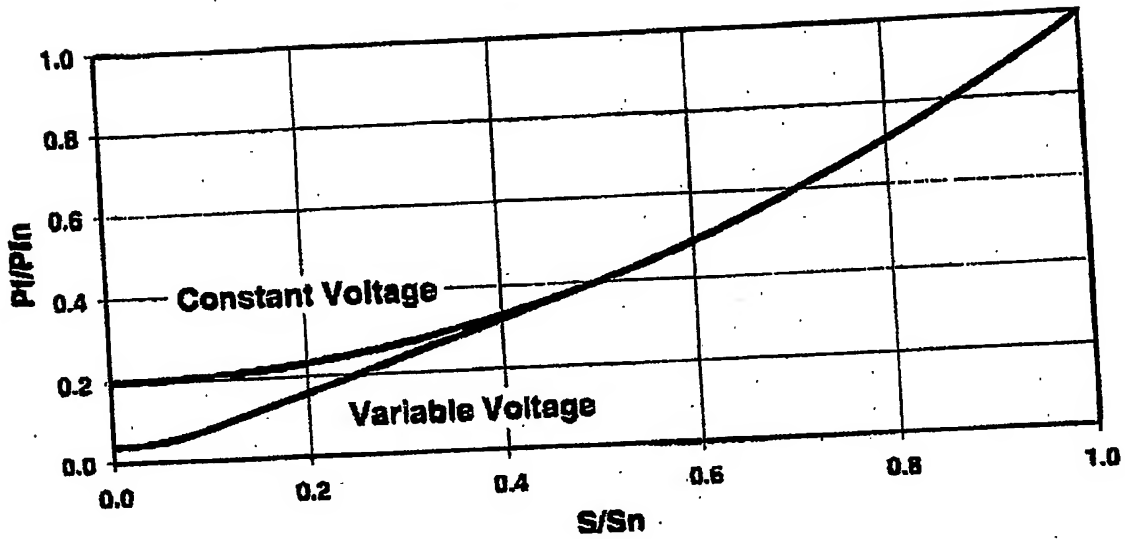## Cable Voltage Optimization
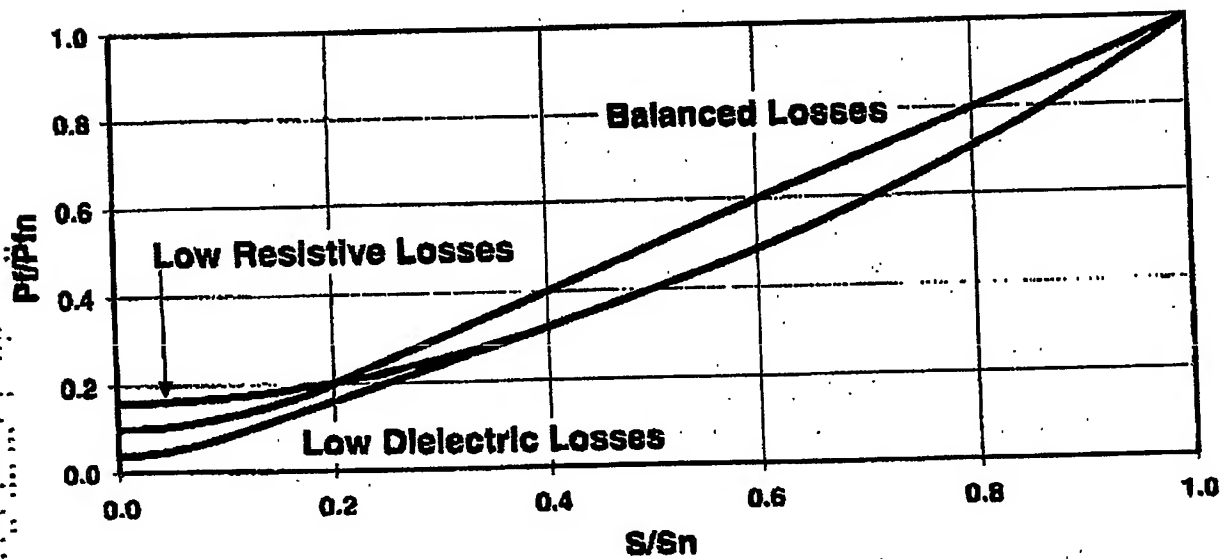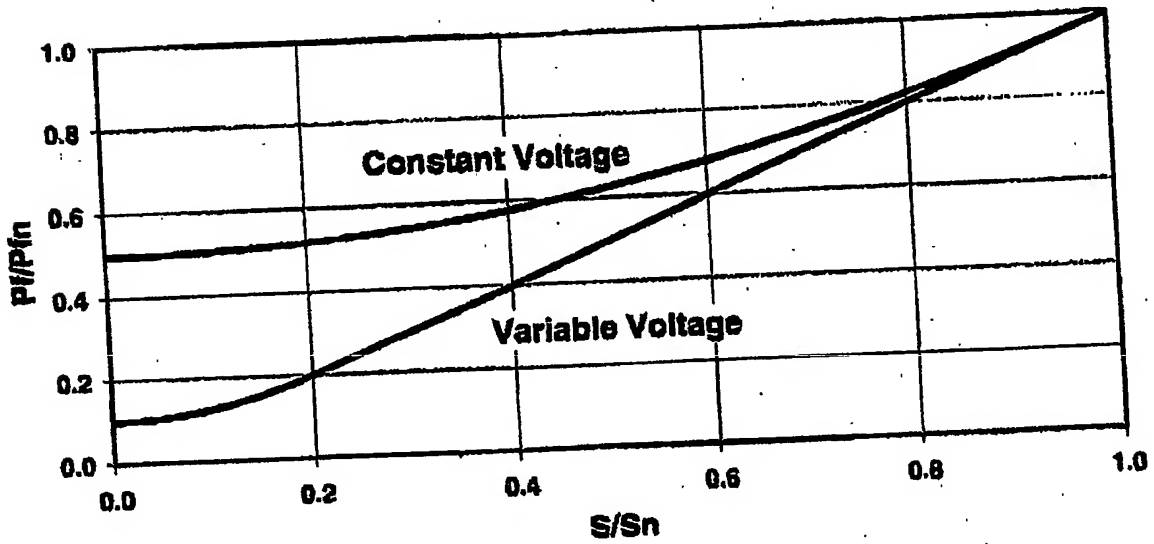

Figure 9

6/8

Low Dielectric Losses
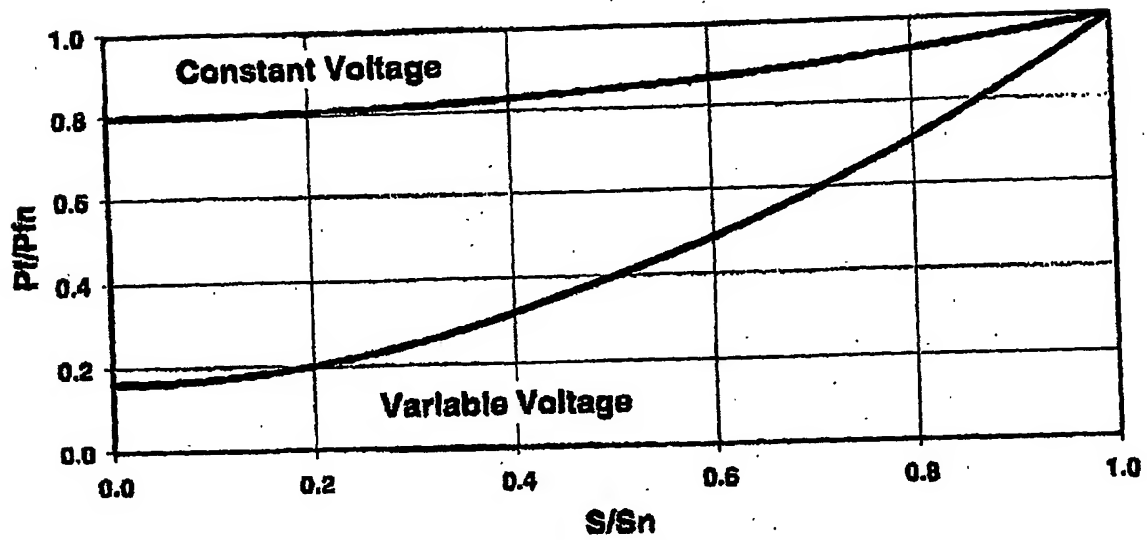

Figure 10

Balanced Losses
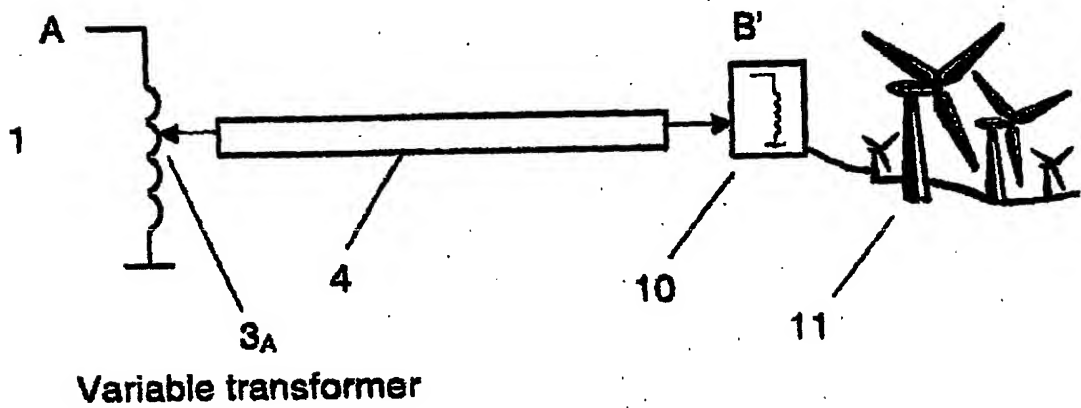

Figure 11

High Dielectric Losses

Figure 12
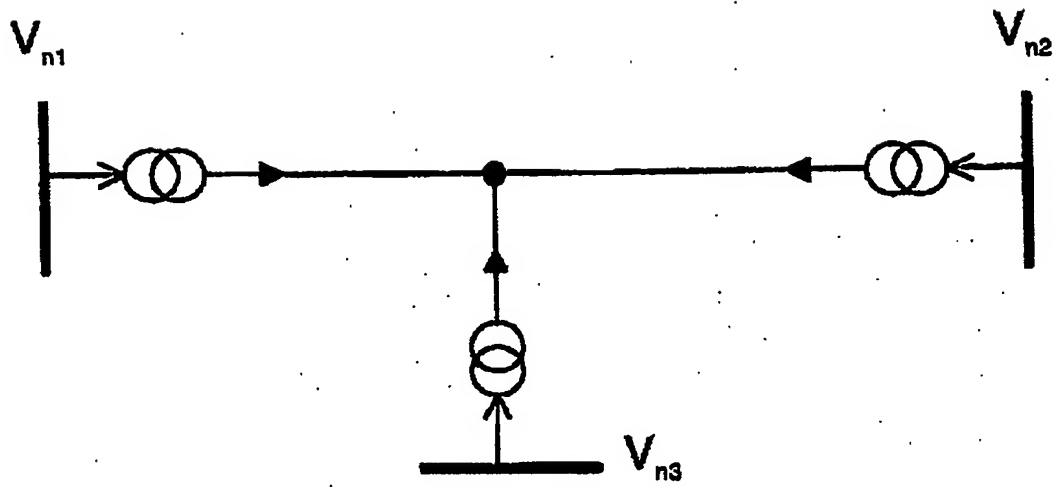

Variable transformer

Figure 13

8/8

Figure 14

125.5 kv V_A

V_B 125.5 kv

T_A 35.5 °C

34.5 °C T_B

25   22   26   21   23$_A$ 20   30   24   23$_B$ 31

Figure 15